

Astroparticle Physics in Hyper-Kamiokande

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Abstract. Hyper-Kamiokande (Hyper-K) is a proposed next generation neutrino experiment, aiming at the measurement which starts at 2027. Hyper-K project includes a high intensity accelerator neutrino beamline at J-PARC and large water Cherenkov far detectors. Each detector will provide the fiducial volume of 0.19 Mt ultra-pure water. Due to its world-largest water volume, superior performance of the new photodetector and the location at deep underground, Hyper-K will also have great capability for neutrino astrophysics and push back the frontiers. Here, the Hyper-K's detector performance for MeV neutrinos will be shown. Then the issues for neutrino astrophysics and our reach will be discussed, i.e., for solar neutrino, supernova burst neutrino and supernova relic neutrino observations.

1. Introduction

Hyper-Kamiokande (Hyper-K, HK) is a next generation water Cherenkov detector planned in Japan [1, 2, 3], as a successor of the Super-Kamiokande (Super-K, SK) experiment [4]. With the dimensions of the 71 m (D) \times 68 m (H), the cylindrical water tank provides the fiducial (total) volume of 0.19 (0.26) million metric tons (Figure 1). They are 8 (5) times larger than that of Super-K. The construction will be done, aiming at the detector operation that starts at 2027. Inner detectors are surrounded by 20-inch diameter 40,000 photodetectors, which have twice larger photon detection efficiency than Super-K photodetectors. 8-inch diameter 6,700 photodetectors are also provided for an outer veto detector to reject cosmic-ray muons. The detector will be located underground at Kamioka mine in Gifu Prefecture, with an overburden of \sim 650 meters of rock, which is equivalent to 1,750 meters of water. Charged particles are detected with the emitted Cherenkov photons. The number of photons and their arrival times on the photodetectors are used to reconstruct the energy and vertex of the particle, respectively. Hyper-K has various physics topics: search for CP violation in neutrinos, precise study of neutrino oscillations including determination of mass hierarchy and θ_{23} octant with beam and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

2. Solar Neutrino

The Sun is burning and emitting neutrinos with the nuclear fusion reactions. They are well described with the standard solar model (SSM) [5]. Our main observation target is the 8B neutrino, since the analysis threshold of our detector will be $E_{vis} > 4.5$ MeV. Here, E_{vis} is the visible energy of the neutrino event in our detector, smaller than the total energy of neutrinos by \sim 1.5 MeV. They are observed through neutrino-electron elastic scattering, $\nu + e \rightarrow \nu + e$. About 130 ν -e scattering events will be observed in a day with 0.19 Mt fiducial volume, while



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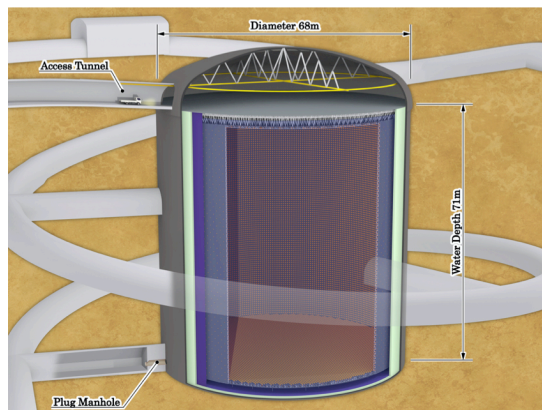


Figure 1. Schematic view of one Hyper-K water Cherenkov detector [1]. We aim the observations start at 2027. The tank will provide the fiducial volume of 0.187 Mt ultra-pure water, with the dimensions of the 71 m (D) \times 68 m (H).

15 ν events/day are observed at SK-I. One of the major motivations of solar neutrino study is the test of the solar model predictions. Because of its high penetration power, neutrino is the unique prove for the current activity of the solar core, where they are generated. Several precise measurements of solar neutrinos would be possible with Hyper-K and its high statistics, e.g. the first measurement of *hep* process neutrino generated in ${}^3\text{He}+p \rightarrow {}^4\text{He}+e^+ + \nu_e$ reaction and the seasonal variation of the ${}^8\text{B}$ neutrino flux. Another major motivation is the study of neutrino properties themselves. Super-K, SNO [6] and several experiments [7, 8, 9] have been measured the neutrino oscillation on the solar neutrinos. A recent result of the oscillation analysis among solar neutrino experiments is following: $\sin^2 \theta_{12} = 0.334^{+0.027}_{-0.023}$, $\Delta m_{21}^2 = 4.8^{+1.5}_{-0.8} \times 10^{-5} \text{ eV}^2$ [10]. On the other hand, a reactor neutrino experiment, KamLAND, also measured the oscillation: $\tan^2 \theta_{12} = 0.56^{+0.14}_{-0.09}$, $\Delta m_{21}^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$ [11]. Figure 2 shows the comparison of these two measurement results and the combined result. The $\sim 2 \sigma$ tension between these Δm_{21}^2 measurements could be tested by Hyper-K. The tension is derived from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which was indicated by Super-K [12]. The asymmetry would arise from the terrestrial matter effect. With Hyper-K, the asymmetry effect can be measured precisely with the large statistics. Assuming the current solar best Δm_{21}^2 parameter, our measurement will be precise enough to separate itself from the current KamLAND best value about 4σ with 10 years observation (Figure 3). The difference of $P_{\nu_e \rightarrow \nu_e}$ in solar neutrino oscillation and $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ in reactor neutrino will be a test of CPT violation at neutrinos. The solar neutrino energy spectrum upturn is also the interesting physics properties. It is predicted by MSW-LMA hypothesis and possibly affected by physics beyond the standard model. The non-zero upturn sensitivity will be about 3σ (4σ) after the 10 years solar neutrino measurement with 4.5 MeV (3.5 MeV) threshold.

3. Supernova Neutrinos

Core collapse supernova explosions are the last process in the evolution of massive stars ($>8 M_{\odot}$). The energy released by a supernova is estimated to be $\sim 3 \times 10^{53}$ ergs and 99% of the energy is carried out by all three types of neutrinos and anti-neutrinos. The detection of supernova neutrinos gives direct information of energy flow during the explosions. From SN1987a, the Kamiokande, IMB, and Baksan experiments observed 25 neutrino events. It proved the basic scenario of the supernova explosion was correct. However, even three decades later the detailed

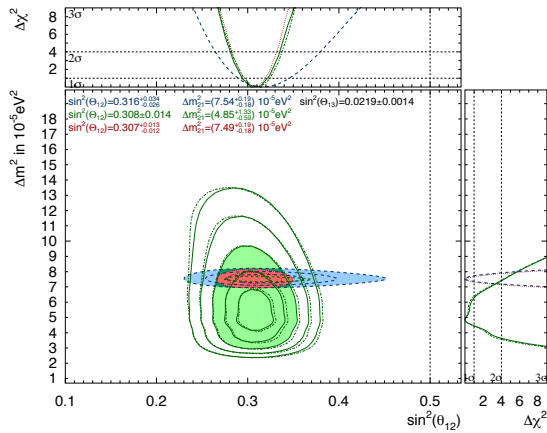


Figure 2. Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 σ lines and 3 σ area are shown[10]. The dashed green line is the combined results of SK and SNO.

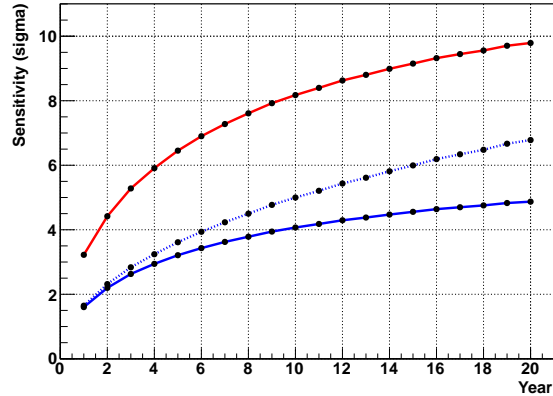


Figure 3. Day-night asymmetry observation sensitivity as a function of observation time. The red line shows the sensitivity from the no asymmetry, while the blue line shows from the asymmetry expected by the reactor neutrino oscillation. The solid line shows that the systematic uncertainty is 0.3%, while the dotted line shows the 0.1% case.

mechanism of explosions is still not known. The observation of new supernova with the large neutrino detector is desired. The multi-messenger observation with visible light, gamma-ray, x-ray, gravitational wave and Hyper-K will also reveal the supernova explosion in details.

The first and direct observation of supernova neutrinos is about the supernova burst neutrinos, which are released in several seconds after its onset of a burst. About 90% of signals at Hyper-K is inverse beta reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). For each full volume of two inner detectors, we expect to see about 49,000-68,000 inverse beta events, 2,100-2,500 ν -e scattering events, 80-4,100 $\nu_e + {}^{16}\text{O}$ CC events, and 650-3,900 $\bar{\nu}_e + {}^{16}\text{O}$ CC events, in total 52,000-79,000 events for a supernova explosion at halfway across our galaxy (10 kpc). The statistical error will be small enough to compare several SN models, and so Hyper-K should give crucial data for further model predictions (Figure 4). A new characteristic modulation of the supernova neutrino flux also can be tested with HK, which the recent computer simulations predict. Recent simulations suggest that the shock wave will be heated efficiently by neutrinos to revival, due to the physical motions in a supernova, Standing Accretion Shock Instability (SASI) or convection, rotation or supernova are the examples. These models also predict the characteristic frequency modulation of neutrino flux, due to the motions in supernovae. The detection of these modulation will prove the neutrino as the driver of supernova explosions. Other topics for astrophysics and particle physics also can be examined, e.g. direct observation of black hole formations and mass hierarchy of neutrinos.

Another observation target is about the supernova relic neutrinos (SRN), produced by all past supernova explosions since the beginning of the universe and diffused. They must fill the universe and their flux is estimated to be a few tens/cm²/sec. SRN contains the information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and the fraction of strange supernova explosions like dim supernovae or black hole formations (Figure 5). Although searches for SRN have been conducted at large underground detectors, no evidence of SRN signals has yet been obtained, because of the small flux of SRN. With incoming detector update, Gd-loaded Super-K (SK-Gd) can be the discoverer of SRN. The number of events in

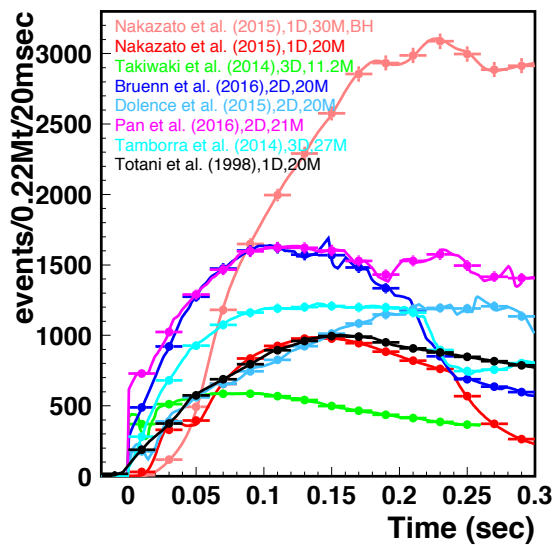


Figure 4. Inverse beta event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst. The error bars shows the statistic error.

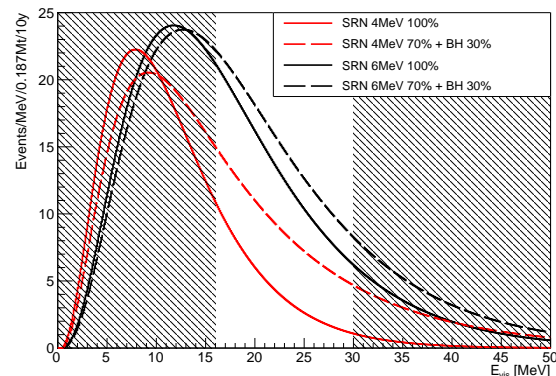


Figure 5. The expected SRN signal. Black line shows the case of supernova neutrino temperature of 6 MeV, and red shows the case of 4 MeV. Solid (dashed) line corresponds to the case, in which all the core-collapse supernovae emits neutrinos with the particular energy (30% of them form black hole and emits higher energy neutrinos with the temperature of 8 MeV). Shaded energy region shows the range out of SRN search window at Hyper-K.

their detector will be 0.8-5 events/year above 10 MeV. Even though, it is still very interesting physics theme to measure and determine the precise flux of SRN. ~ 70 SRN events are expected at 16-30 MeV with 1 tank and 10 years observation. The significance will be 4.2σ and enough for confirming the discovery. Further studies for astrophysics and particle physics topics will be performed.

4. Summary

Hyper-Kamiokande is a next generation large water Cherenkov detector. Several studies are being performed, e.g. photosensor R&D, design and physics optimization. Astrophysical neutrino measurement is one of the features of Hyper-K. We will provide the unique information for solar, supernova burst and supernova relic neutrinos. Hyper-K will play a crucial role in the next neutrino physics frontier for both of particle physics and neutrino astrophysics.

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